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Many of the problems of operating an AUV (autonomous underwater vehicle) can be reduced to one of navigation: How accurately do you know where you are? Navigational precision determines the ability to follow track lines, the ability to map a target to world coordinates, and ultimately, even determines the areas where you are willing to operate the vehicle.

This paper presents the technique used for long baseline acoustic navigation by REMUS (Remote Environmental Measuring UnitS), a low cost AUV developed by the Oceanographic Systems Laboratory (OSL) of the Woods Hole Oceanographic Institution. Adapting the traditional long base line approach to this vehicle presents a complex problem because it must be low power, low cost, and small in size, and in addition must work in a shallow water environment.

The REMUS system uses a single data acquisition system and DSP to interrogate and receive multiple transponders in a sequential manner. It uses spread spectrum technology which reduces the impact of multi-path in the shallow water environment. A moored pair of acoustic transponders whose coordinates are determined using differential or P-Code GPS allow the vehicle to navigate in world coordinates. The DSP minimizes the hardware requirements, thus lowering the associated hardware cost, size, and complexity.

This paper describes the techniques used and provides results of this system using frequencies in the 20-30khz band, giving a range of up to 1500 meters in water 4 meters deep, and also 10-15khz band, giving a range of up to 7000 meters in waters 14 meters deep.

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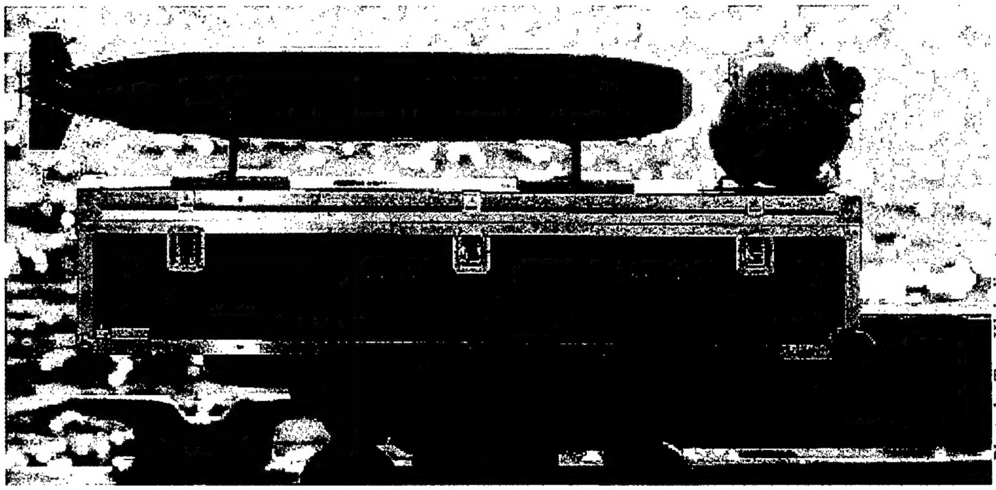

Photo by Tom Kleindinst

Sequential, Long Baseline Navigation for REMUS, an Autonomous Underwater Vehicle

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Keywords: AUV, Autonomous Underwater Vehicle, Navigation, Acoustic Navigation

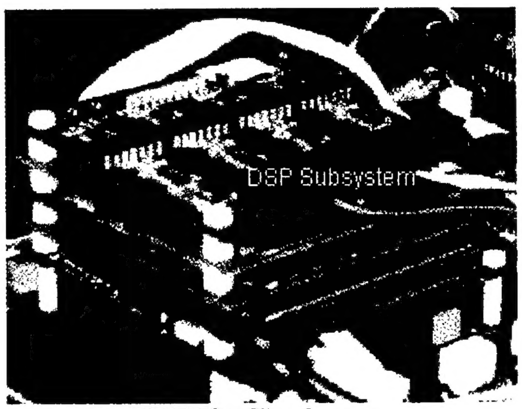
1. INTRODUCTION

Most autonomous underwater vehicles may be rapidly characterized by how they navigate. More so than size, endurance, or instruments, navigational capability often determines what a vehicle can accomplish. Unfortunately, all of the available navigation systems have some sort of limitation. For example, dead reckoning, even with expensive and power hungry instrumentation, is subject to drift. GPS, the terrestrial answer, penetrates the ocean only a few centimeters, thus requiring a vehicle to surface for fixes, and to dead reckon between fixes. For this reason, various forms of acoustic navigation have

often been the preferred means for accurately determining position. Typical systems utilize a network of seafloor transponders, which receive on a common interrogation signal from the vehicle and reply using unique signals. This approach has the advantage of providing nearly simultaneous range information to all transponders, but requires the vehicle to carry multiple receivers. This hardware usually takes the form of a bulky bank of receiver boards, in order to cover all of the expected transponder signals. However in addition to their large size, the fixed frequency tone bursts of these systems are highly susceptible to multi-path in the shallow water regime, thus resulting in unacceptable performance.

2. HARDWARE

In 1994, the Oceanographic Systems Laboratory began development of REMUS[1][2] (Remote Environmental Measuring UnitS), low cost autonomous underwater vehicles designed for operation in the coastal ocean. The initial vehicle had only a crude dead reckon navigation capability, but built into the system was sophisticated DSP based hardware for acoustic navigation that had the potential enabling the vehicle to navigate using both ultra-short and long base line techniques. In subsequent years, OSL developed first this ultra-short baseline (USBL) navigation system, then the long baseline (LBL) system.



REMUS DSP sub-system

Interestingly, the original plan for REMUS had been based around a traditional hardware based filtering system. However, before the first vehicle was built it was realized that low power digital signal processors (DSP's) could achieve the same functionality, with much greater flexibility. Under previous programs funded by ONR and DARPA, OSL had developed the high-speed data acquisition system and the software necessary to capture signals from a single transponder. For REMUS the system was configured so that the four channel receiver electronics were multiplexed between a four channel nose mounted planar array used for ultra short baseline navigation, and a single omni-directional bottom mounted transducer, used for long baseline navigation. The USBL implementation of this system has been described in other papers[3][4].

One advantage of the DSP based approach is that different frequencies can be used without having to change the filtering hardware. REMUS works in the 20-30 kHz region and in the 10-15 kHz region, depending on the application. Changing frequencies requires changing the transmit and receive hardware, but the DSP hardware remains unchanged. The entire DSP stack draws a little over two watts.

3. DETECTION

Long baseline navigation works by having the vehicle interrogate multiple, widely spaced transponders of known position. The round trip travel time, when appropriate corrections are made for hardware delays and the sound speed of the water, determines range. This range puts the vehicle at some point on a sphere surrounding the transponder. When the ranges to two transponders are known, the intersection of the respective spheres defines a circle. Since the depth of the vehicle is known, and the vehicle has a priori knowledge of the transponders depths, this further reduces the intersection to two points, one on either side of a baseline connecting the two transponders. This ambiguity could be resolved with a third transponder, but if the approximate position of the vehicle is known, it can be used to select which of the two answers is correct. This also

avoids the problem of having an over determined solution, since various errors make it is unlikely that either of the two points will fall exactly on the sphere defined by the range from the third transponder.

Traditional hardware based detection uses a hardware filter and a threshold comparator. For the DSP based approach used in REMUS, detection is done using a matched filter programmed into the DSP. The received signal is digitized, demodulated, and run through a filter whose transfer function is equivalent to the transfer function of the ideal signal. The matched filter is realized digitally in the frequency domain by multiplying the FFT of received signal with the conjugate of the reference (or ideal) signal. The inverse FFT (IFFT) is performed on the product to convert the filtered output back into the time domain. There, a thresholding technique is used to select the earliest arriving peak. A second check is done to verify that the peak is sufficiently unique, since transponders that share the same interrogation frequency may also respond. However, since they respond with the wrong code, theirs should be a poor match.

When operating in the 25 to 27 kilohertz region, the system can capture a window of 160 milliseconds, which represents a range bin of about 120 meters. When operating down in the 10 kHz regime, the system samples at a slower rate, and the capture window is twice as large. If a good match is not found within the range bin, the system can, using multiple pings, scan a larger range hunting for the target. Normally, once "lock" has been achieved, the vehicle maintains a range gate, and range results outside expected values are rejected. As the age of the last good fix increases, so does the uncertainty, and the size of the gate.

4. ADAPTING LONG BASELINE FOR SEQUENTIAL OPERATION

Hardware based detectors operate in parallel: the net is interrogated, and all transponders respond. Since each transponder must respond using a unique frequency, a receiver board is required for each transponder. If the vehicle is expected to traverse a large geographic area, then a large number of transponders must be deployed to provide acceptable coverage, and thus a large number of receiver boards are required as well. REMUS often uses six low frequency transponders (10-15khz) to run 20 km straight line transects at the LEO-15 site off of Tuckerton, NJ. If REMUS were to use a conventional hardware based receiver, this configuration would require six receiver boards, an unacceptable burden for a vehicle of REMUS' size. However, because REMUS sequentially interrogates the transponders, it requires only a single receiver, resulting in a substantial savings of both space and power. While this approach could be accomplished in the analog domain, the filtering hardware saved would be offset by the additional hardware needed for the switching. In any event, moving the processing into the digital domain makes the system more flexible, and enables the use of spread spectrum signals, rather than simple tone bursts.

When using LBL navigation, the vehicle selects the optimum pair of transponders for each leg. Once the range to one transponder is determined, the vehicle switches to the other transponder. This requires loading a different reference waveform into the system, and then repeating the acquisition process with the second transponder. Once the range to the second transponder is determined, the system can calculate the vehicle location. This requires factoring in the distance the vehicle moved between the two fixes. This is estimate is normally made by the vehicle's dead reckoning navigation system. On vehicles equipped with a bottom lock Doppler navigation system, this computation is quite accurate, even when a substantial amount of time elapses between the fixes. Those not so equipped count prop turns, and are thus less accurate, but typically the second fix occurs within a few seconds of the first, so the error is small.

At this point the system has the required inputs to determine the vehicle's position: the positions of the two transponders, the horizontal ranges from the vehicle to the two transponders (after converting from slant range), and the estimate of the distance the vehicle moved between fixes. This final term can be eliminated by adding that motion as an offset to the first transponder's position. For example, if the estimate is that the vehicle moved 20.2 meters at 61 degrees true between fixes, add that offset to the first transponder's position, and treat the sum as the actual transponder position. After correcting for the estimated motion, the solution can be determined by simple triangulation. Since the result involves a square root term, there are two answers (or none). The range from the current estimated vehicle position to each of these solutions is computed, and the one with the shorter distance is selected as the answer.

Once a solution is available, an updated vehicle position can be computed by adding the distance that the vehicle has moved since the second fix was received, typically a couple of meters, since the acoustic signal processing takes a little over a second. The system now reverts to interrogating the first transponder. Once ranges are available to both transponders, position updates can occur with each new transponder fix.

5. SOURCES OF ERROR

There are a number of sources of error in the position calculated by the sequential long baseline system. Most are inherent in any long baseline system. First is the accuracy of placement of the transponders themselves. Typical errors of differential GPS (D-GPS) are on the order of 10 meters. However even the distance from the GPS antenna (typically at the bridge) to the deployment position on the vessel (off the stern) can contribute an additional offset to that error.

In shallow water, transponders are moored just by lowering them over the side, and it is not necessary to survey them in after the fact. In some operational scenarios, the REMUS mission is pre-programmed, and the transponders are taken to these pre-programmed positions and deployed. This incurs another error, since it may be difficult for the pilot to get to the *exact* position. Sometimes REMUS is updated with the actual transponder position, other times it is not.

Sound speed can also be a significant error source. In shallow water, depth alone does not cause a significant variation in sound speed, however temperature and to a lesser degree salinity, can and will cause significant changes in sound speed, including changes in these values as a function of depth. Based on the usual formulas for the speed of sound[5], variations of about a meter per second per milliliter/liter of salinity can be expected, and about 3 meters per second per degree Centigrade change in temperature. Given that complex temperature and salinity fronts may be found in the shallow water regime, precise calculations can be problematic. At ranges of 1500 meters or more, errors in these values can result in substantial errors in range, and thus position. If the vehicle collects conductivity and temperature data as part of its survey, post processing of this data could allow the vehicle's position to be recomputed with greater precision.

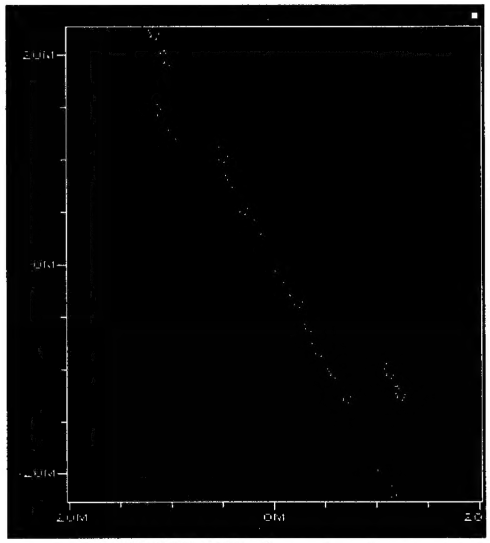
Poor geometry of the vehicle with respect to its transponders can result in significant errors as well. When the ranges from the transponder intersect at shallow angles, then minor errors in range can result in large changes in position. This occurs when the vehicle is either near the baseline running through the two transponders, or at large distances from the transponders relative to their distance apart.

In general working near the baseline is a bad idea as there are a number potential errors, and proper operation cannot be assured. If the acoustic distance between the transponders is less than the calculated distance (i.e. the value derived from the latitudes and longitudes), then when the vehicle is on the baseline, the measured sum of the two ranges from the vehicle to the transponders (as determined by the acoustics) will be less than the distance between the transponders, a geometric impossibility. Since no answer is possible, acoustic navigation will have no solution and the vehicle will be forced to dead reckon. When crossing the baseline in this situation, the vehicle enters a "dead zone" where there is no answer. Once it emerges out the other side new fixes are possible, and because the dead reckoned position shows the vehicle has crossed the baseline, the acoustic system will recognize that the vehicle has crossed the baseline as well.

This is preferable to the situation where the acoustic distance between the transponders is *greater* than that derived from the latitudes and longitudes. In this case, the vehicle still appears to be some distance from the baseline when it is actually crossing it. Since after crossing, the ranges start to increase, the vehicle appears to be moving away from the baseline. However, in this situation because the system selects the closest solution, it never detects the crossing, and the fixes give the appearance that the vehicle is traveling backwards.

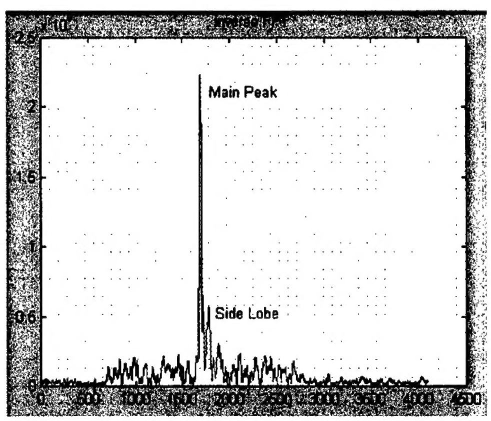
When the vehicle is running nearly perpendicular to the baseline, this situation is easily detected, but when the direction of travel is nearly parallel, detection is much more difficult. We have witnessed both phenomenon. Naturally, using a third transponder eliminates this problem.

Another source of error is that range is a function of the actual path the sound takes between the vehicle and transponder. In tests in San Diego harbor, the water was about 4 meters deep, and the vehicle range was as much as 1500 meters. The



REMUS LBL fixes showing discontinuities (4 meters water depth, 650 meters range to both transponders)

concept of a direct path under these circumstances is at best dubious. In actual practice, the ranges appear to be very consistent and yet there are short-term discrete jumps of a few meters. The figure above illustrates this jitter in 4 meters of water at a range of 650 meters from both transponders. For this geometry, the difference between the direct path and the one with a single reflection is about 12 centimeters. To get the jumps shown above, there would need to be a change from zero to about 12 reflections. Realistically, a more Gaussian distribution would be expected. Furthermore, the range would always be



Plot of Inverse FFT data showing side lobes

greater, not larger *and* smaller as is the case above. Instead, the suspicion is that this is due to interference causing some attenuation of the main peak, and at the same time amplifying a side lobe, thus causing the algorithm to select the wrong peak. This is currently under investigation.

The measurement of the amount that the vehicle moves between transponder fixes is a source of error. Typically, the actual distance moved is quite small, and the residual error after estimation smaller still, however when there is a long time between fixes, the accumulated error can grow. For vehicles that are equipped with bottom lock Doppler, the distance traveled is generally quite accurate, however magnetic compass errors can be significant, thus the estimated position may be rotated several degrees relative to the actual position. Most long baseline systems don't correct for this vehicle motion at all, since

the distance the vehicle moves between the different ping arrivals is at most a few seconds. However, a vehicle traveling at four knots can move two or three meters in that time, and this error creates an ambiguity in position.

Currently the implementation corrects for the distance the vehicle moves between interrogations. A future improvement will provide a correction for the distance a vehicle moves between the time a ping is transmitted and when the reply is received.

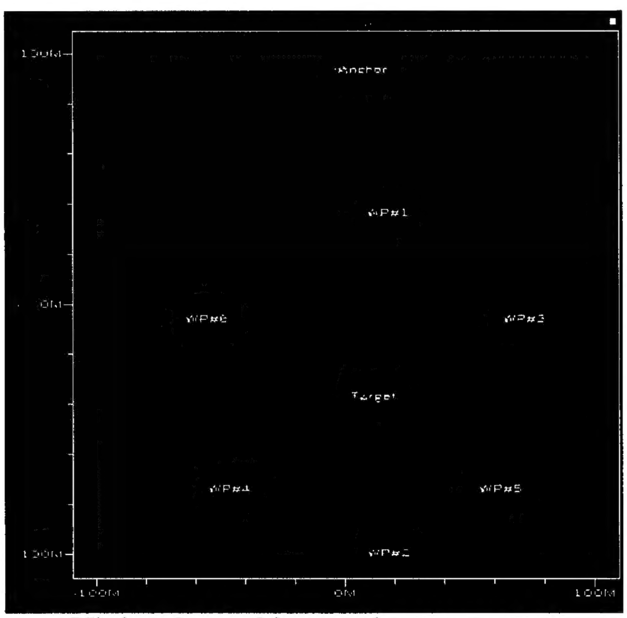
6. RESULTS

During September of 1997, REMUS' navigational system was tested at Naval Amphibious Base, San Diego, CA. These tests measured the vehicles ability to follow a trackline at a variety of speeds and its ability to locate targets using its side scan sonar. Both these tests measure the vehicles navigational capabilities, and thus the accuracy of the sequential long baseline system.

The trackline following test was conducted by having the vehicle swim a box with 400-meter sides. Multiple laps were run, with each lap around the box taking approximately 16 minutes. The root mean squared (RMS) crosstrack error relative to the intended track of the vehicle was measured, with the first and last fifty meters disregarded as the vehicle was making the transition to a new track. In multiple runs on the open ocean, the average RMS error was 3.1 meters.

This was a total system test, that tested both the navigational system as well as the vehicle's control system. Since the vehicle uses only a type one loop to keep itself on a given trackline (this is *not* the heading loop), strong cross track currents will push it off the line somewhat

In a related test, the repeatability of the system was tested by having the vehicle navigate past a known target, first by swimming two clockwise laps, then two counterclockwise laps, in each of 3 directions separated by 60 degrees as shown above. The target was approximately 700 meters from the navigation transponders, in about 7 meters of water. After this mission the target was located in the sidescan records, and the resulting positions compared (The vehicle provides navigation information to the sidescan so that a targets latitude and longitude may be easily determined).

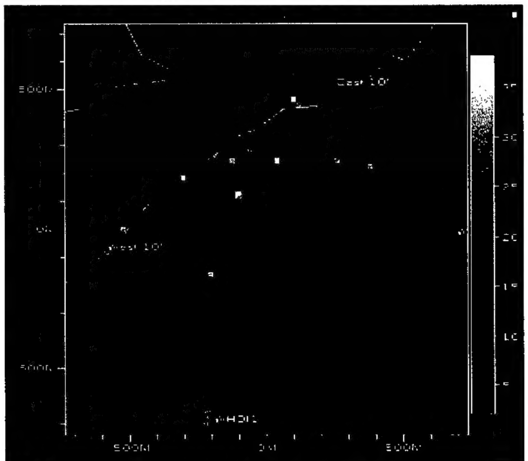


Mission plan used for targeting accuracy test

The target was found in 47 out of 48 possible attempts (in the one miss, the target was believed to be in the near nadir region under the vehicle where the sonar is effectively blind). For these 47 attempts, the two-dimensional circular error of position was 3.7 yards. Statistically, 63 percent of position fixes will fall within a circle of this radius, and 98 percent will fall within a circle two times this radius.

Unfortunately, both of these tests are *relative* tests. Even with differential GPS, it is difficult to reduce the errors in transponder placement sufficiently to provide proper ground truth for these experiments. However, additional tests with greater precision are planned for this summer. These should provide a measure of the absolute accuracy of the system.

For many of its missions, REMUS starts offshore at one of two transponders, navigates in and mows the lawn along the shoreline, working its way out. System performance of the navigation system is part of the data stored for later analysis. Among these is a measurement that is referred to as the "in-band signal to noise ratio".
This is the ratio of the size of the time domain peak to the other values in the immediate vicinity; i.e. it is a measurement of



Inband SNR plot showing better results in shallow water at longer range from the buoys

Symbol indicates transponder position

the uniqueness of the peak. Obviously, a higher value is better. What is unusual is that we have consistently obtained values that indicate better performance at longer ranges, even when those longer ranges are in very shallow water (about 3 meters) close to shore. In the plot above, the water depth ranges from 3 meters near the beach to 5 meters off shore. We are investigating this phenomenon.

7. OTHER APPLICATIONS

The small size and repeatability of this system make it appropriate for a number of diverse applications. For example, objects that are detected using REMUS' sidescan sonar could be targeted for more detailed reconnaissance in subsequent missions. These follow up missions (involving REMUS or some other platform) could use the same navigation system. If the same acoustic net is used, then many of the navigation errors (such as exact transponder positioning) are eliminated, since they will be identical for all missions. Others, such as sound speed are affected only by the changes that occur between missions.

Because of its low power and small size, placing this system on a different platform, either a diver or another vehicle, would not present a significant technical challenge. The interface to another vehicle might be an RS-232 link. The interface to divers might be a sequence of LED's that indicate the range and direction to a sequence of targets, thus allow them to easily return to known positions.

8. CONCLUSIONS

The digital approach of sequential long baseline navigation uses less hardware than that of traditional analog methods. Also, by use of DSP processing techniques, more sophisticated signals can be used that decrease the affects of multi-path signals.

9. ACKNOWLEDGEMENTS

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